Comparison between hourly simulation and bin-method for the seasonal performance evaluation of electric air-source heat pumps for heating

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Abstract

Air-source heat pumps in heating mode are characterized by performances strongly dependent on the value of the outdoor air temperature. The Italian standard UNI/TS 11300-4 indicates, for the evaluation of a heat pump seasonal efficiency, a method based on the local bin distribution of the external air temperature. The aim of this paper is to test the bin-method proposed by UNI/TS 11300-4 by comparing the results obtained through this method with the results deducted by using a more accurate dynamic simulation of the system. The heat pump Seasonal Coefficient Of Performance (*SCOP*) is calculated by means of a dynamic simulation code, written in MATLAB, in which hourly climate data distributions defined by CTI for different Italian towns are introduced as input data together with the thermal characteristics of the building. The thermal winter behaviour of the building is introduced in the models by using the Building Energy Signature. In the paper the values of the seasonal indexes $SCOP_{on}$ and $SCOP_{net}$ obtained by means of the bin-method and the dynamic hourly simulation, both for mono-compressor and inverter-driven heat pumps, in the service of several buildings placed in different Italian climates, are evaluated and compared to each other. Different buildings and different climate data are used in order to highlight the main conditions which are responsible for the difference between the predictions obtained with the bin-method and the results obtained by using the dynamic hourly simulation. The results presented in this paper show that the predictions of the bin-method tend to be in agreement with the results of the dynamic simulations based on the Test Reference Year only in particular conditions. The observed discrepancies in terms of *SCOP* between these two approaches can reach 23%, varying with the climate data and with the type of heat pump considered.

1. Introduction

The diffusion of air-source heat pumps in heating systems and for domestic hot water production has recently increased since these devices use aero-thermal energy, which the Directive 2009/28/EC (European Parliament, 2009) recognizes as renewable energy. Moreover, thanks to their relative cheapness and to the air availability, air-source heat pumps are often used in energy retrofit of buildings to replace conventional heat generators. The performance of an air-source heat pump depends on building loads and on the outdoor air temperature, which is variable during the heating season; therefore, the evaluation of the heat pump seasonal efficiency should be performed through a dynamic simulation of the system. As an alternative, the Italian standard UNI/TS 11300-4 (UNI, 2012) suggests the use of the bin-method to obtain the Seasonal Coefficient Of Performance (*SCOP*) of an air-source heat pump.

The evaluation of a heat pump seasonal efficiency has been analysed in several recent studies (Kinab et al., 2010; Francisco et al., 2004; Sarbu et al., 2014 and Madonna et al., 2013). The present Authors have recently developed a mathematical model able to evaluate, through the bin-method, the *SCOP* of electric air-to-water heat pumps integrated by electric heaters (Dongellini et al., 2014) as well as a MATLAB code for the hourly simulation of air-to-water heat pump systems working in heating mode (Naldi et al., 2014).

In this paper the model based on the bin-method (Dongellini et al., 2014) is used together with the model based on the dynamic simulation (Naldi et

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al., 2014) in order to compare the values of the Seasonal Coefficient Of Performance of different heat pump typologies, building thermal demands and climates. The analysis has been conducted by considering both on-off and inverter-driven mono-compressor air-source heat pumps, integrated by electric heaters as back-up system, in the service of buildings placed in different Italian climates.

The results obtained in this work highlight that the bin-method and the hourly dynamic simulation of a heating plant based on an air-source heat pump give comparable results in terms of seasonal performance coefficients; the larger relative difference in terms of *SCOP* is observed for high values of the bivalent temperature in cold climates.

2. Simulation

2.1 Dynamic simulation

The hourly simulation of the heat pump heating system is carried out through the MATLAB code described in (Naldi et al., 2014). The main input parameters of the model are: the hourly values of the outdoor air temperature during the heating season, the hourly values of the thermal power required by the building, the heat pump and thermal storage volume technical data.

In the present study the hourly climate data defined in the Test Reference Year by CTI for three Italian towns (Naples, Bologna and Milan) are used.

If the heat pump has an on–off mono-compressor system, the heat pump technical data in input are: the Temperature Operative Limit (*TOL*), the values of the heat pump power and Coefficient Of Performance (*COP*) at the temperature of the hot water produced by the heat pump and for different values of the outdoor air temperature (T_{ext}). *COP* is the parameter which quantifies an electric heat pump efficiency and it is defined as the ratio between the thermal power delivered and the corresponding electric power needed by the heat pump.

If the heat pump is provided with an inverter compressor, the power and *COP* input data are given in correspondence of different inverter frequencies.

The code evaluates for each hour of the heating season several parameters, including: the maximum power available from the heat pump, the energy supplied by the heat pump and, if needed, by the back-up system (electric heaters), the mean temperature of the water in the thermal storage, the electric energy used by the heat pump and by the back-up system.

The code then evaluates the values assumed by the $SCOP_{net}$ and $SCOP_{on}$ defined by UNI EN 14825 (UNI, 2013) as follows:

$$SCOP_{net} = \frac{Q_{HP}}{E_{HP,us}} \quad (1)$$

$$SCOP_{on} = \frac{Q_b}{E_{HP,us} + E_{BK}} \quad (2)$$

where Q_{HP} is the total thermal energy delivered by the heat pump during the heating season, $E_{HP,us}$ is the electric energy used by the heat pump, Q_b is the total thermal energy required by the building, and E_{BK} is the electric energy used by the back-up system.

2.2 Bin-method

The Italian standard UNI/TS 11300-4 utilizes the bin-method for the evaluation of an air-source heat pump seasonal performance. A bin is the number of hours, during a certain period of time, in which the external air has a temperature within a fixed interval, which is 1 K wide and centred on an integer value of temperature. The standard UNI/TS 11300-4 evaluates the bin trend of an Italian location by assuming a normal distribution of the outdoor air temperature, obtainable starting from the local values of outdoor design temperature (T_{des}), monthly average external air temperature and daily global solar radiation on horizontal plane. The bin distribution for the heating season in Milan (45.28 °N, 9.11 °E), Bologna (44.29 °N, 11.20 °E) and Naples (40.50 °N, 14.15 °E) has been evaluated as indicated by the Italian standard, considering the heating season from October 15th to April 15th for Milan and Bologna and from November 15th to March 31st for Naples. The obtained bin profiles are shown in Fig. 1-3 (blue colour), together with the bin trends derived from the hourly values of the outdoor air temperature according to the Test Reference Year (TRY) defined by CTI (red colour) for the same locations.

It is evident from Figures 1-3 that the bins calculated by using the CTI's TRY and those evaluated by the method proposed by UNI/TS 11300-4 are different.

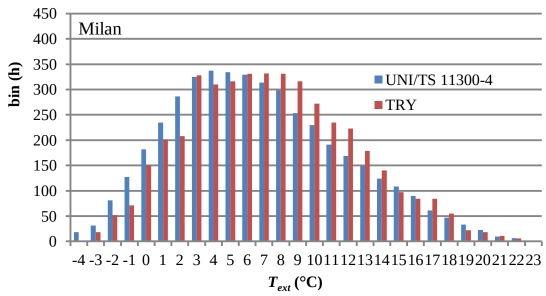

Fig. 1 – Bin profiles for Milan

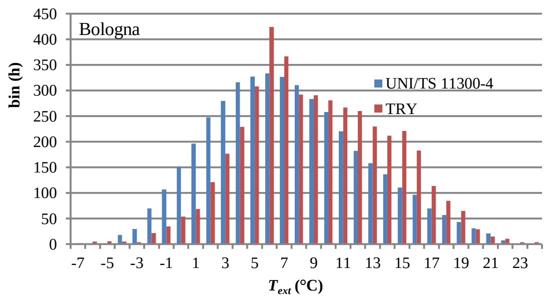

Fig. 2 – Bin profiles for Bologna

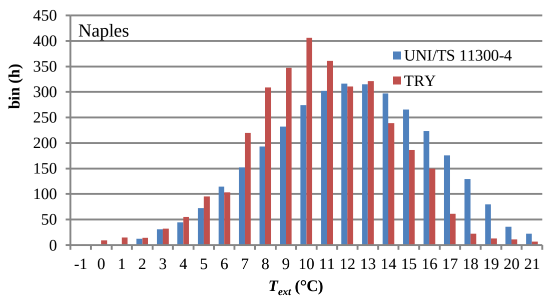

Fig. 3 – Bin profiles for Naples

For instance, the bin profiles evaluated according to UNI/TS 11300-4 are characterized by an average temperature of 6.8 °C in Milan, 7.3 °C in Bologna and 12.1 °C in Naples, versus the values of 7.4 °C (Milan), 9.2 °C (Bologna) and 10.7 °C (Naples) obtained by using the CTI's TRY.

2.3 Building Energy Signature

The thermal energy required by the building in correspondence of each bin is evaluated, as UNI/TS 11300-4 suggests, by means of the Building Energy Signature (*BES*), which is the straight line giving the power required by the building as a function of the external air temperature (i.e. red dashed line in Fig. 4).

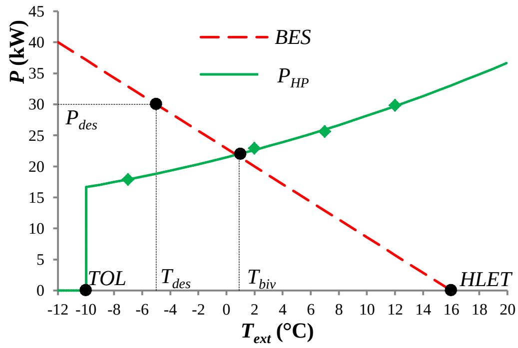

Fig. 4 – Building Energy Signature and heat pump power as function of the external air temperature

In order to consider different building loads and their effect on heat pumps' seasonal performances, several *BES* lines are here considered, by fixing the value of the external temperature where the building heating demand becomes zero (*HLET*: Heating Limit External Temperature) and by varying the value of the building design load (P_{des}) in correspondence of the outdoor design temperature (T_{des}). Indeed, once two points in the temperature-power diagram are known (e.g. (0, *HLET*) and (T_{des}, P_{des})), a *BES* straight line is univocally identified.

In order to compare the results obtained from the bin-method with those derived from the dynamic simulation, the hourly values of the energy required by the building in the dynamic simulation are calculated, in each case studied, by means of the same *BES* line as that used in the simulation with the bin-method.

2.4 Heat pump technical data

Both in the dynamic simulation and in the bin-method, the thermal power delivered by the heat pump, P_{HP}, is obtained by interpolation of the technical data given by the heat pump manufacturer, for fixed temperatures of the outdoor air and of the hot water produced.

The green solid line in Fig. 4 is an example of the characteristic curve of an electric air-source on-off mono-compressor heat pump (ON-OFF HP), plotted as a function of the external air temperature, for a fixed temperature of the hot water produced. The heat pump characteristic curve is stopped in correspondence of the *TOL*.

The intersection between the Building Energy Signature and the heat pump characteristic curve is called the balance point, and the corresponding external air temperature is called the bivalent temperature (T_{biv}). In correspondence of T_{biv} the heat pump thermal power matches the thermal load of the building; when the external air temperature becomes lower than T_{biv} the heat pump is not able to completely satisfy the building heating demand, so that the back-up system must be activated; if T_{ext} is higher than T_{biv}, on the contrary, the heat pump power exceeds the building request, and the ON-OFF HP has to start on-off cycles, with efficiency losses.

For an Inverter-Driven Heat Pump (IDHP), the heat pump capacity P_{HP} is a function not only of the outdoor air and hot water temperatures, but also of the inverter frequency; T_{biv} is defined as the intersection between the *BES* line and the heat pump capacity at full load, namely at the maximum inverter frequency.

If the outdoor air temperature is higher than T_{biv}, an IDHP can reduce its working frequency in order to follow the building load (partial load condition), until the minimum frequency is reached. IDHPs must activate the on-off cycles only if the building load is lower than the heat pump capacity at the minimum inverter frequency, so that the on-off cycles are strongly delayed.

The characteristic curve of the *COP* of the heat pump at declared capacity is obtained from the manufacturer data, as described in (Naldi et al., 2014) and in (Dongellini et al., 2014).

Fig. 5 shows the characteristic curves at full load of the ON-OFF HP and the IDHP used for the simulations presented in this work, obtained by interpolation of the manufacturer data in correspondence of a temperature of the hot water equal to 35 °C (i.e. for radiant panels heating systems). In the same graph the corresponding curves of the electric power $P_{HP,us}$ used at declared capacity by the heat pumps are also plotted. $P_{HP,us}$ is obtained as the ratio between P_{HP} and the *COP* at declared capacity. From Fig. 5 it can be noticed that the selected heat pumps are characterized by similar values of the power delivered at full load with the same outdoor temperature conditions.

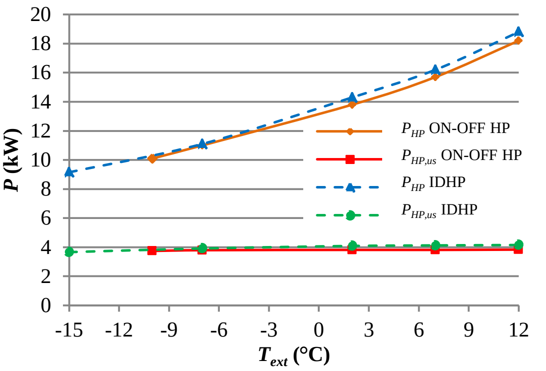

Fig. 5 – Thermal power delivered and electric power used by the heat pumps at full load

Table 1 shows the IDHP power and *COP* data given by the manufacturer for several inverter frequencies and external air temperatures (for a fixed hot water temperature equal to 35°C).

Table 1 – IDHP power (in kW) and (*COP*) at declared capacity, for different inverter frequencies and external temperatures

	Frequency (Hz)				
***T*ext (°C)**	**85**	**69**	**53**	**36**	**20**
-15	9.15 (2.50)	7.43 (2.57)	5.71 (2.56)	3.94 (2.42)	2.17 (1.98)
-7	11.10 (2.84)	9.06 (2.94)	7.00 (2.95)	4.86 (2.81)	2.67 (2.32)
2	14.30 (3.50)	11.60 (3.61)	8.93 (3.64)	6.28 (3.54)	3.42 (2.91)
7	16.20 (3.93)	13.20 (4.08)	10.30 (4.16)	7.23 (4.06)	3.94 (3.36)
12	18.80 (4.53)	15.30 (4.73)	11.90 (4.85)	8.38 (4.73)	4.60 (3.95)

By comparing the data shown in Table 1, it is evident that, while the values of P_{HP} obviously decrease with the reduction of the inverter frequency, the values of the *COP* become higher until a frequency around half the maximum is reached, after which they decrease.

3. Results and discussion

The mathematical models described in (Naldi et al., 2014) and in (Dongellini et al., 2014) have been applied to evaluate the seasonal performances of different heat pumps in Milan, Bologna and Naples. The reported main seasonal coefficients of performance of the heat pump, ($SCOP_{net}$, $SCOP_{on}$) are calculated by fixing *HLET* equal to 16°C and varying the design load of the building for a fixed temperature of the hot water produced (35°C).

First of all, the coherence of the bin-method with the dynamic simulation has been tested. Starting from the CTI's TRY for Milan, a comparison has been made in terms of *SCOP* by using the dynamic simulation and the bin-method in which the bins have been calculated by using the same TRY data used in the dynamic simulation. The data in Fig. 6 show the *SCOP* obtained with the ON-OFF HP and IDHP for several buildings in Milan. As can be seen in Fig. 6, the achieved results in terms of $SCOP_{on}$ and $SCOP_{net}$ with the two different approaches are in agreement with each other; the maximum discrepancy recorded is about 9% on $SCOP_{on}$ of the ON-OFF HP in the service of a building with a value of T_{biv} equal to 6.6°C (rightmost point on the red and blue curves, Fig. 6a). This means that the bin-method is able to give an accurate prediction of the seasonal performance coefficients of the heating plant in good agreement with the more accurate results available after the dynamic simulation of the system, if the two methods use the same climatic data as input.

The results reported in Fig. 7-9 show the difference, in terms of the main seasonal performance coefficients ($SCOP_{net}$, $SCOP_{on}$), obtained by following the bin-method proposed by UNI/TS 11300-4 and the dynamic simulation based on the CTI's TRY for buildings located in Milan, Bologna and Naples, respectively. It is evident, since these approaches are based on climatic data not exactly coincident, as can be seen in Fig. 1-3, that the difference in *SCOP* values is larger than that in Fig. 6. More in detail, the two approaches tend to show larger differences in terms of $SCOP_{on}$ in correspondence of large bivalent temperatures, i.e. with under-sized heat pumps with respect to the building thermal demand. Indeed, the differences in terms of $SCOP_{on}$ are mainly related to the back-up activation which, under similar conditions, is relevant at larger values of T_{biv}. At low values of T_{biv} the influence on the *SCOP* values of the climatic differences is combined with the effect due to the increase of the compressor on-off cycles, caused by the heat pump over-sizing with respect to the building thermal load. The effect of the on-off cycles is obviously stronger with the ON-OFF HP with respect to the IDHP, where the modulation capacity of the compressor delays the starting of on-off cycles.

The on-off condition determines a degradation of a heat pump performance quantified by multiplying the *COP* value at declared capacity by the *COP* correction factor, f_c, defined as:

$$f_c = \frac{CR}{1 - C_c + C_c\ CR} \quad (3)$$

where *CR* is the heat pump capacity ratio and C_c is the degradation coefficient, set by the standards equal to 0.9 in absence of more specific manufacturer indications.

As is evident from the results shown in Fig. 7, since the bin distributions derived from the TRY of Milan and UNI/TS 11300-4 method are very similar (the average temperature from TRY is 0.6 °C higher than the UNI/TS 11300-4 value (see Fig. 1)), the values of *SCOP* obtained with the two methods tend to be very close to each other.

In Bologna (see Fig. 8) higher *SCOP* are obtained with the dynamic simulation with respect to the results obtained with the bin-method, since CTI's TRY data present an average temperature 1.9 °C larger with respect to the bin distribution calculated through UNI/TS 11300-4. It is evident by comparing Fig. 7 and Fig. 8 that in Bologna the differences in terms of $SCOP_{on}$ obtained by using the dynamic simulation and the bin-method are larger with respect to the differences obtained in Milan. In addition, for a fixed value of the bivalent temperature, the difference in terms of $SCOP_{on}$ is larger for the ON-OFF HP than for the IDHP. The difference in terms of $SCOP_{net}$ is very limited both for Milan and Bologna. In Fig. 9 the same evaluation has been made for Naples. In this case the dynamic simulation and the bin-method give very similar results in terms of $SCOP_{on}$ and $SCOP_{net}$ both for ON-OFF HP and IDHP. When the bivalent temperature is reduced (over-sized heat pump) the *SCOP* increase due to the hotter climate is reduced by the increase of the number of on-off cycles and the seasonal performance coefficients tends to become equal by using the dynamic simulation (hotter outdoor temperature, larger number of on-off cycles) and the bin-method based on UNI/TS 11300-4 distribution (colder outdoor temperature, lower number of on-off cycles).

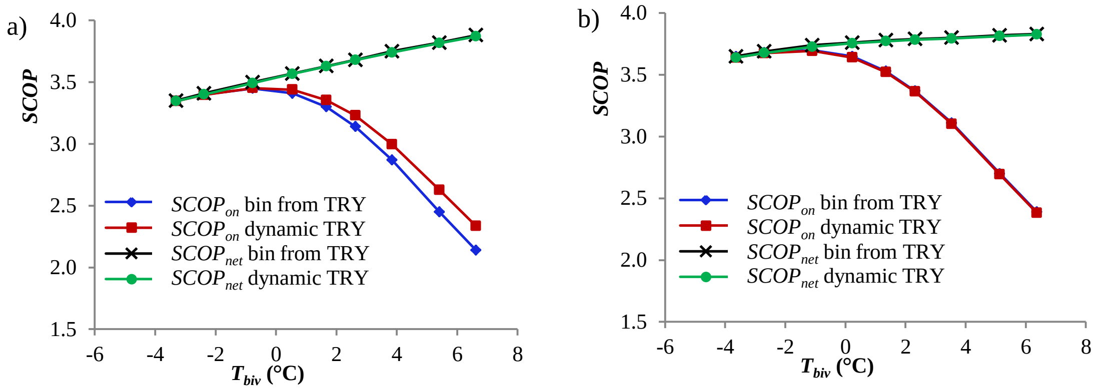

Fig. 6 – *SCOP* as function of T_{biv} from the dynamic and bin simulations, ON-OFF HP (a) and IDHP (b), Milan

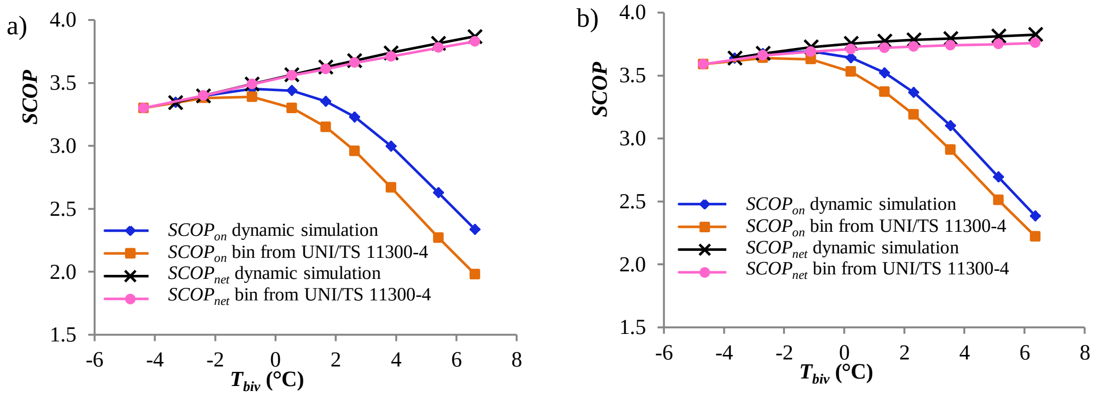

Fig. 7 – *SCOP* as function of T_{biv} from the dynamic simulation and bin simulation from UNI/TS 11300-4, ON-OFF HP (a) and IDHP (b), Milan

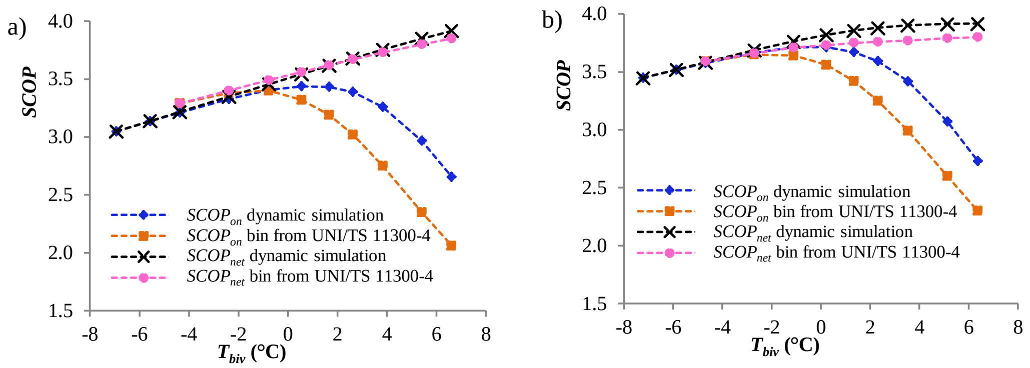

Fig. 8 – *SCOP* as function of T_{biv} from the dynamic simulation and bin simulation from UNI/TS 11300-4, ON-OFF HP (a) and IDHP (b), Bologna

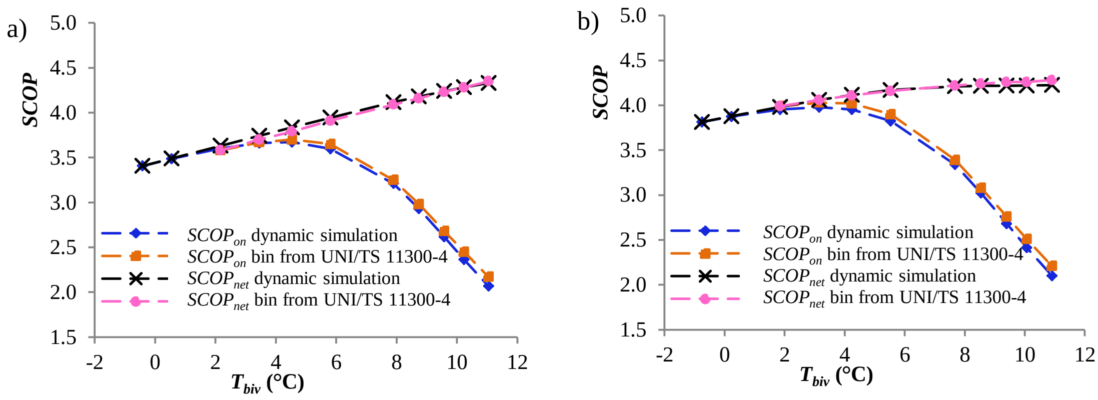

Fig. 9 – *SCOP* as function of T_{biv} from the dynamic simulation and bin simulation from UNI/TS 11300-4, ON-OFF HP (a) and IDHP (b), Naples

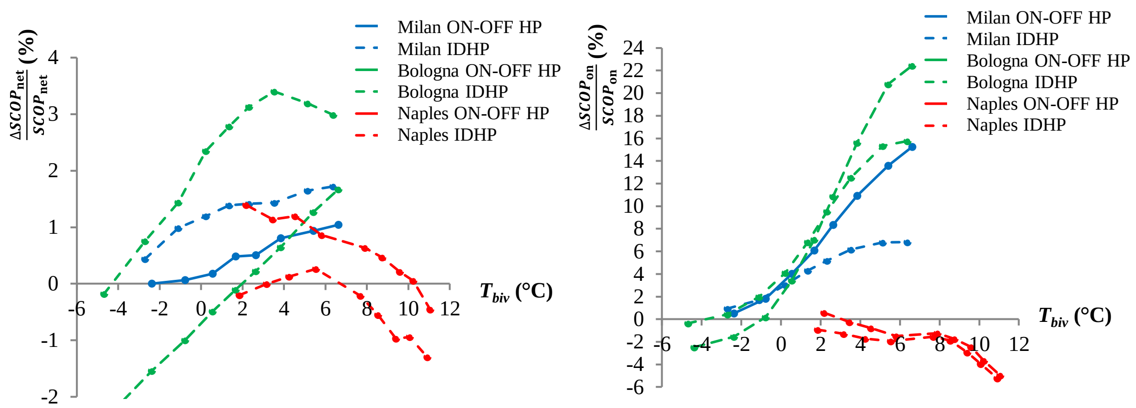

Fig. 10 – Relative differences on the seasonal indexes as functions of the bivalent temperature

Fig. 10 shows, as function of T_{biv}, the difference in terms of *SCOP* obtained from the dynamic simulation and the bin-method. The choice of the calculation method influences especially the value of $SCOP_{on}$, whose relative difference reaches 22.4% (ON-OFF HP in Bologna with T_{biv}=6.6 °C), while the maximum relative difference on $SCOP_{net}$ is always very limited (i.e. 3.4% for IDHP in Bologna with T_{biv}=3.5 °C). These results highlight that the larger relative difference in terms of $SCOP_{on}$ is generally observed for the ON-OFF HP, with high values of the bivalent temperature.

4. Conclusions

In this paper a comparison between the results obtained by means of the bin-method proposed by UNI/TS 11300-4 and the dynamic hourly simulation of a heating system based on an air-source heat pump is shown in terms of seasonal coefficients of performance (*SCOP*) in different Italian locations. The numerical results highlight that the bin-method is able to give numerical results in good agreement with the results obtained by means of a dynamic hourly simulation especially for low bivalent temperature values (over-sized heat pumps) both for ON-OFF HPs and IDHPs. However, for large values of the bivalent temperature (i.e. under-sized heat pumps with respect to the building thermal loads) the two methods give different results in terms of *SCOP*. More in detail, for typical Italian climate data, the maximum deviation between the predictions of these two methods in terms of $SCOP_{on}$ can reach 23% for ON-OFF HPs under-sized with respect to the building thermal loads. On the contrary, in terms of $SCOP_{net}$ the difference is always less than 4% both for under-sized and over-sized ON-OFF HPs and IDHPs.

5. Acknowledgement

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6. Nomenclature

Symbols

BES	Building Energy Signature
C_c	*COP* degradation coefficient
COP	Coefficient Of Performance
CR	heat pump capacity ratio
E	electric energy (kWh)
HLET	Heating Limit External Temperature (°C)
IDHP	Inverter-Driven Heat Pump
ON-OFF HP	ON-OFF Heat Pump
P	power (kW)
Q	thermal energy (kWh)
SCOP	Seasonal Coefficient Of Performance
T	temperature (°C)
TOL	Temperature Operative Limit (°C)
TRY	Test Reference Year
f_c	*COP* correction factor for on-off cycles

Subscripts

BK	of the back-up system
HP	of the heat pump
b	of the building
biv	bivalent
des	design
ext	of the external air
net	of the heat pump only
on	of the heat pump and back-up system
us	used

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